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A Compact Low-Power High-Isp Thruster for Microsatellites

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ABSTRACT

Busek Co. Inc. completed delivery of flight-qualified colloid thrusters for NASA's ST7 mission in May 2008. This effort has led to development of variants of the technology suitable for small satellite applications. Colloid thrusters operate by electrostatically accelerating charged droplets of an electrically conductive ionic liquid, and are capable of providing a high degree of throttling and variable Isp. Life tests of the ST7 thrusters have demonstrated over 3000 hours of continuous operation with no deterioration in performance. A further benefit is that the colloid thrusters do not present high pressure and fire safety hazards common to many other propulsion systems- the propellant is nonreactive and is typically stored at less than 20psig.

The thrusters presented have a target maximum thrust of 1 milliNewton with 0.1-1.0 milliNewton throttling. They are designed to operate in the Isp range of 400-1000s, consume a maximum of 15W (including power supply losses), and be self-contained in a 10cm x 10cm x 20cm package requiring only power and thrust command inputs. The package contains sufficient propellant for 500 hours operation at maximum thrust, yielding total impulse of 1800 seconds capable of imparting almost 200 m/s delta V to a 10kg satellite.

INTRODUCTION

In electrospray thrusters (also called colloid thrusters), a controlled mass flow of propellant is fed, via surface wetting or capillary tubes, to a zone subjected to a high voltage electric field. The propellant is at higher potential than a facing electrode, called the extractor. Because of this extracting potential, the propellant is atomized into charged droplets, which in turn form an electrospray beam, producing thrust. The potential of the beam can be further increased by means of an accelerator electrode. A schematic is illustrated in Figure 1. The thrust throttling capability in electrospray thrusters is significant: by varying the propellant flow rate and the beam voltage within reasonable values, it can deliver a thrust ratio of 20 or better[1]. Selection of appropriate propellant flow rate and beam voltage have the further benefit of influencing the size and charge of the emitted droplets, permitting control of Isp as well, with Isp and absolute thrust tending to be inversely correlated.

Electric propulsion, generally with significantly greater specific impulse than more conventional approaches such as chemical or cold gas, is a highly compelling propulsion source for satellites. Most electric propulsion, however, is suitable only for larger spacecraft since their performance scales down poorly at smaller sizes and lower thrust levels.

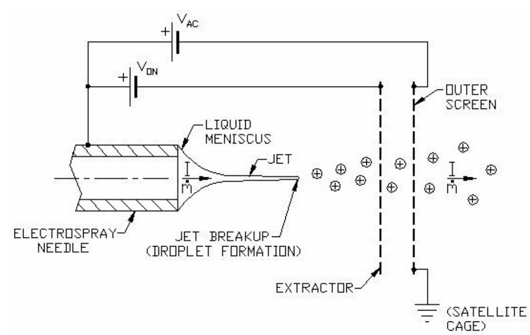

Figure 1: Schematic of Electrospray Thruster

Electrospray thrusters, alternately, are demonstrated to scale well to the size, mass, and thrust levels suitable for small spacecraft. Thruster performance does not experience the efficiency and life penalties typical of scaled-down versions of larger thrusters. A single electrospray emission site is some tens of microns in diameter, provides up to 5 microNewtons thrust, and consumes approximately 10mW. Single emission site thrust efficiencies are in the 80% range, and scale-up via multiplexing does not indicate any efficiency impact from emission site interactions. In reality, with primary system efficiency being driven by power supply conversion losses, scale-up to milliNewton thrust levels, comprised of some hundreds of emission sites, provides highly favorable improvements in overall system efficiency.

Busek Co. Inc., in May, 2008, completed delivery of a pair of colloid thruster clusters for the NASA ST7 mission. These thrusters, selected for their unique capabilities in precision thrust control and low-noise operation, are the culmination of a six-year and nearly $20M development effort by Busek characterizing thrust performance, including lifetime, plume geometry, spacecraft contamination, spacecraft charge neutralization, power electronics design, thruster throttling, thermo-vacuum testing, vibration testing, shock testing, radiation exposure, and thruster controls. The basic technology is fully-vetted and has been NASA flight qualified.

The NASA ST7 thrusters, however, were developed with only a specialized application in mind: ultraprecise thrust for maintaining spacecraft position for large-scale interferometry applications. They are not well-suited for many other missions. The fundamental technology of electrospray thrusters, however, is highly attractive for the reasons mentioned previously. Because of this, and the considerable electrospray thruster expertise acquired in the ST7 development effort, Busek has pursued a number of colloid thruster variants suitable for more general applications, and, in particular, highly attractive for small satellites.

This paper, after providing a more detailed view of the NASA ST7 thrusters, shall provide an introduction to Busek's other electrospray thrusters under development. They include the following:

- 1mN class Mixed Mode Planar Thruster
- 1mN class Valveless Thruster
- 1mN class Variable Isp Slit Thruster

NASA ST7 THRUSTERS

The NASA Space Technology 7 (ST7) mission is a technology demonstration mission seeking to test femtoNewton force measurement sensors developed by the European Space Agency (ESA)[2], and to use these force measurements to command microthrusters to maintain spacecraft position relative to an internal, freely-floating test mass[3]. Selected performance requirements for the microthrusters are:

Table 1: ST7 Performance Requirements

Parameter	Requirement
Thrust	*5-30 μN*
Thrust Resolution	*0.1 μN*
Thrust Noise	*0.1 μN /√Hz from 1 to 30 mHz*
Lifetime	*3300 Hrs*

A photograph of one of the flight units is shown in Figure 2. As previously mentioned, the ST7 mission requirements focused primarily upon ultraprecise performance, necessitating a large suite of power and control electronics, vital signs monitoring, and electrical isolation of multiple independent thrusters and propellant feedsystems.

Figure 2: NASA ST7 Cluster of Four (4) Independently Operated Colloid Thrusters with 90 Days' Propellant Supply, Four (4) Power Processing Units (PPU), Field Emission Cathode, and Digital Control and Interface Unit (DCIU)

Demonstrated thrust throttling is shown in Figure 3. Thrusters are capable of multiple startup/shutdown cycles for bang-bang operation, or can operate continuously while modulating thrust over large throttling range. In the case of the NASA ST7 thrusters, thrust resolution can be adjusted to 0.01 μN precision and steadily maintained. Figure 4 provides an example of measured thrust noise while operating at intermediate thrust levels, indicating levels of ≈0.01 μN/√Hz between .001 and 2 Hz.

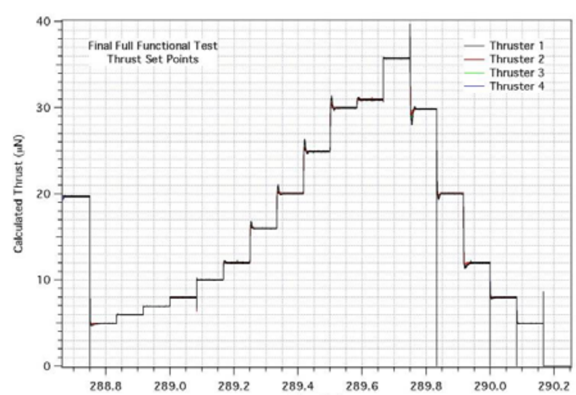

Figure 3: Illustration of Dynamic Range of Thrusters, Operating 5 to 38.5 μN (overlay of 4 thrusters operating simultaneously)

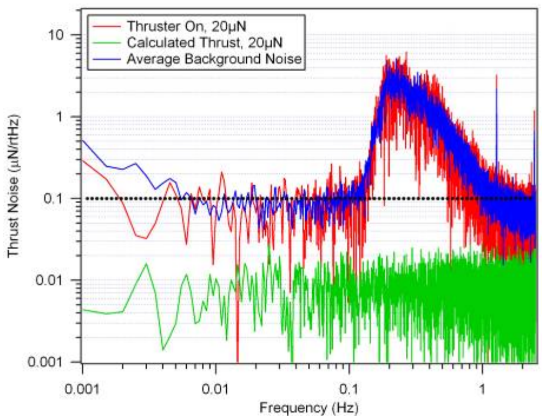

Figure 4: Measured Thrust Noise, Using Busek-Developed Magnetically Levitated Thrust Stand

This work was supported by NASA/JPL under Contract No. NAS7-1407.

1mN CLASS MIXED MODE PLANAR THRUSTER

The 1mN class mixed mode planar thruster is an extension of the single capillary electrospray emission site principal used in the NASA ST7 thrusters. This approach utilizes a planar, propellant-wetted surface as an initiation site for multiple electrosprays, providing much higher thrust in a small package, but with a penalty of variable droplet size affecting maximum attainable Isp as well as some loss of throttling fidelity. By relaxing the NASA ST7 requirements and increasing the number of emission sites, this thruster design shall be capable of delivering thrust up to several milliNewtons in a package the size of one to two sections of a nano-sat (10cm x 10cm x 10cm). Target lifetime of the development model for the currently-funded effort is 300 hours, and it is expected that application of life-extending techniques from the NASA ST7 design could provide lifetime >1000 hours.

The thruster head is shown in Figure 5. The emission region is ≈3mm diameter. Electrode and isolation components increase the envelope to ≈15mm thick x 40mm diameter.

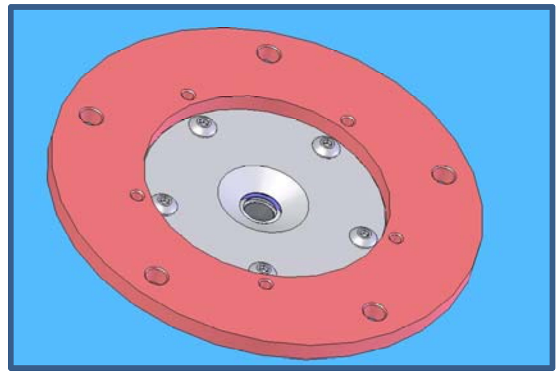

Figure 5: View of a Planar Emitter Surface Colloid Thruster Under Development

Current development efforts are focused on emitter optimization, ejected plume characteristics, and time of flight measurements. The time of flight measurements, accompanied with direct thrust measurements, provide validation of thrust and Isp. To date, the thruster performance characteristics reported are based on measured thruster voltage and current.

Figure 6 depicts a typical test run achieved during testing of the planar colloid emitter. During this specific test, the beam voltage remained constant while the flowrate to the thruster was modulated.

Figure 6 demonstrates that a single planar emitter source is capable of delivering up to 200µN of thrust from an emitter surface of less than 3mm diameter. The data suggest that the specific impulse achieved can range from 250 seconds to over 1000 seconds. This remains to be verified by other means, and if corroborated confirms that the thruster is capable of a wide range of Isp and corresponding thrusts. Thruster efficiency during testing was confirmed at ≈75%.

This work is supported by the Missile Defense Agency (MDA), and managed by the Air Force Research Laboratory (AFRL) under Contract No. HQ0006-05-C-7235.

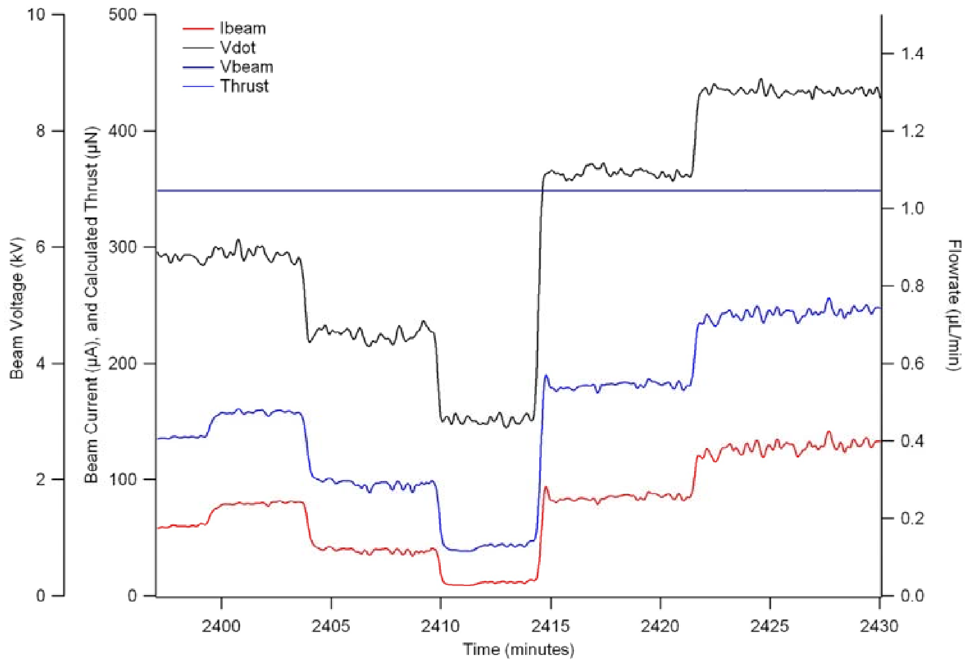

Figure 6: Typical Colloid Thruster Response to Variations in the Delivered Flowrate to the Planar Emitter. The estimated thrust was calculated based on beam current (Ibeam), and voltage (Vbeam) after each test run. The thrust indicated here does not take into account losses associated with plume divergence and droplet voltage loss due to electrospray emission cone formation. Note the thrust levels of 200µN for a single emitter, as opposed to 3-4µN per emitter for the NASA ST7 thrusters.

1mN CLASS VALVELESS THRUSTER

In a further simplification of the baseline colloid thruster design, Busek is reducing the complexity of the planar colloid thruster, described earlier, by converting to a self-regulating feed system, eliminating the need for active flow control and pressurized propellant storage. The device, shown in Figure 7, relies on electrostatic forces and surface tension effects to supply propellant to the planar emitter at a regular rate.

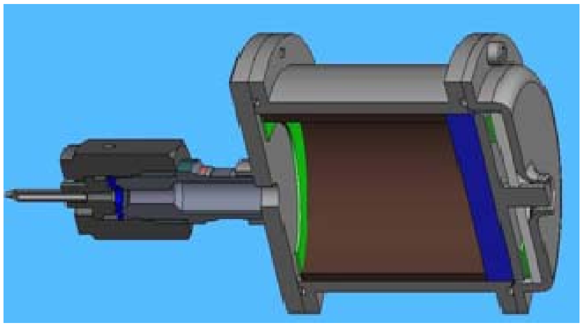

Figure 7: Cross-sectional View of the Proposed Capillarity Feed System and Planar Emitter. Tank walls are porous to promote capillary transport of propellant to the thruster emitter. The extraction grid is not shown

There are many technical advantages of converting to such a feed-system. Firstly, the system has no moving parts, making it very reliable. Secondly, the removal of a valve and associated electronics yields a more compact thruster unit capable of delivering similar thrust levels as the planar thruster.

The solution to the primary obstacle for the valveless thruster, propellant isolation during ground operations and launch, has already been demonstrated. Isolation is important because the ionic liquid propellant's hydrophilic characteristics lead to absorption of water from environmental humidity. Adsorbed water in the propellant boils off when exposed to vacuum, interfering with proper thruster performance. Busek has demonstrated a simple, non-mechanical technique for isolating the bulk propellant from absorbing contaminants while on the ground. The isolation technology has been demonstrated via helium leak detectors to be leak proof to 10^{-10} torr*L/sec.

This thruster will operate by the modulation of a single thruster parameter, emitter voltage. Above some "turn on" limit the voltage will be sufficient to draw propellant to the surface of the planar emitter and form a multiple-emission electrospray.

This work is supported by a NASA/JPL Phase I SBIR under Contract No. NNX08CD10P.

1mN CLASS VARIABLE Isp SLIT THRUSTER

The design goals of the Slit Colloid Thruster program are to develop a thruster that is efficient (of the order of 70%), has an I_{SP} in the range of 300 to 1000 seconds, and has a thrust output on the order of 1 mN or larger. In order to achieve these goals, the slit colloid thruster is designed to maximize the number of emission sites per unit emission length in a geometry promoting electrical field uniformity along the entire emission region. This is accomplished by using a linear sharp edge for the emission region, and by minimizing electric field strength variations, precise I_{SP} control is possible.

When propellant is fed to the emission region, and an appropriate voltage difference is applied between the slit and the facing extractor, multiple emission sites develop. The emission sites are anchored to the edges, each performing similarly the individual sites of the needle emitters described previously. Both extraction voltage and propellant flow rate determine the number of emission sites, and ultimately thrust and I_{SP}.

Preliminary testing has consisted of studying a single slit emitter to optimize basic design elements, such as geometry, propellant transport, and operating parameters. Figure 8 shows initial data including calculated thrust and I_{SP}. Thrust is calculated from measured beam voltage and beam current. According to these initial results, a single slit emitter is capable of thrust from approximately 50 µN to 200 µN. An array of 6 such emitters is expected to reach the initial goals of this research, which is expected to be verified with direct thrust and I_{SP} measurements on Busek's magnetically levitated thrust stand.

In order to perform direct thrust and I_{SP} measurements, a self-contained thruster must be constructed which includes bellows, emitters, PPU, DCIU, and valve: Figure 9 shows the engineering model (front panel removed to show bellows) currently under construction. This slit colloid thruster array (Figure 9) will be confined to a 10cm x 10cm x 30cm volume.

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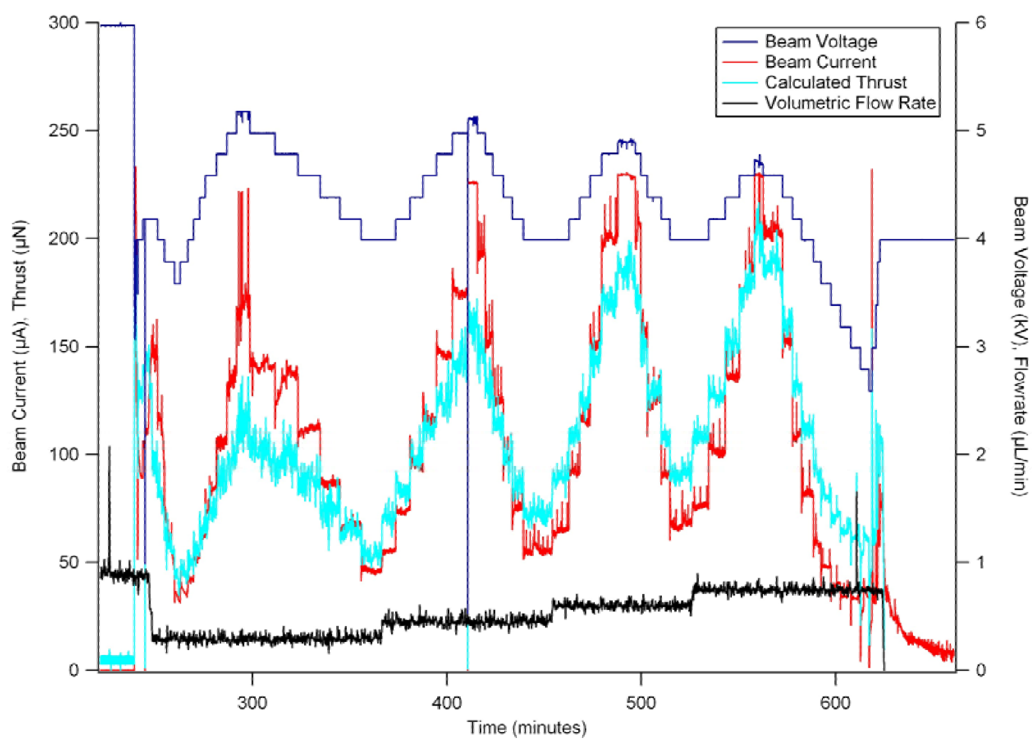

Figure 8: Beam Voltage, Flowrate, and Calculated Thrust from a Run Using a Single Slit Colloid Thruster. Slit emitter is approximately ½" x ½" x 2" dimensions.

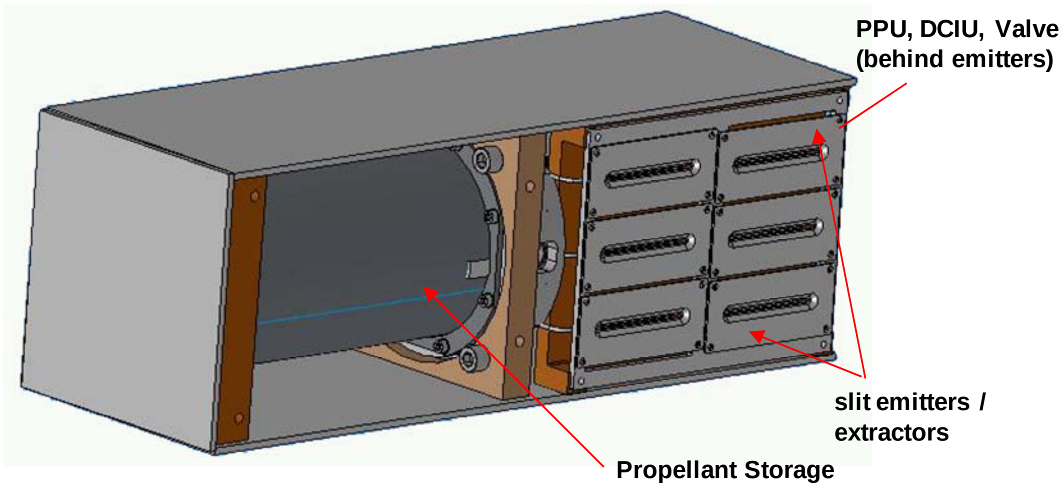

Figure 9: Engineering Model of the Slit Colloid Thruster Array Featuring a 10cm x 10cm x 30cm Envelope

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